EFFECTS OF DIFFERENTIAL SPILL VOLUME AND ENTRAINMENT DEPTH ON SURVIVAL AND INJURY OF JUVENILE SALMONIDS AT THE ICE HARBOR DAM SPILLWAY, SNAKE RIVER

Contract No. DACW68-02-D-0002
Task Order 0013

July 2005

EFFECTS OF DIFFERENTIAL SPILL VOLUME AND ENTRAINMENT SURVIVAL AND INJURY OF JUVENILE SALMONIDS AT THE ICE HARBOR DAM SPILLWAY, SNAKE RIVER

Contract No. DACW68-02-D-0002
Task Order 0013

Prepared for

U. S. ARMY CORPS OF ENGINEERS
WALLA WALLA DISTRICT
201 North Third Avenue
Walla Walla, Washington 99362

Prepared by

NORMANDEAU ASSOCIATES, INC.
1921 River Road
Drumore, Pennsylvania 17518

And
John R. Skalski
University of Washington
Seattle, Washington

Normandeau Job Number 18880.013

July 2005

EXECUTIVE SUMMARY

HI-Z tagged (balloon tag) Chinook salmon smolts, *Oncorhynchus tshawytscha* were released at two depths (8 ft and 20 ft above the ogee in March 2004) within Spillbays 1 and 5 at two spill volumes (5.1 kcfs and 11.9 kcfs) and at two spill volumes (4.3 kcfs and 11.9 kcfs) and at three depths (3 ft, 8 ft, and 20 ft above the ogee) within Spillbay 5 in May 2004 to: (1) assess the effects of differential spill volume on fish condition and survival, (2) estimate direct survival probabilities within ≤± 0.03, 90% of the time, and (3) better understand the injury mechanisms to assist in possible spillway or flow deflector modifications for enhanced fish survival. Matching control group of fish was released through the juvenile fish bypass facility. Fish release locations were selected to coincide with the depth of naturally migrating salmonids exiting the spillbays; the range of spill volumes selected through each spillbay was that deemed to cover spill volume that may be used in practice. Spillbay survival data collected in 2003 at comparable hydraulic conditions were also statistically analyzed along with 2004 data to increase understanding and knowledge.

Recapture rates (physical retrieval of alive and dead fish) of both treatment (97.1% to 99.3%) and control (96.7% to 98.0%) groups were high.

Survival estimates (48 h) differed somewhat between March (low Tailwater elevation) and May (high Tailwater elevation) 2004 releases, most likely due to differences in spill volumes and spill patterns and their attendant hydraulic conditions in the stilling basin. Survival probabilities were relatively high (≥0.979, SE=0.011-1.0, model constraints precluded calculation of standard errors for latter estimates) for all test conditions in March with the highest survival (1.0) at 11.9 kcfs in both spillbays. At high Tailwater elevation in May, differences in survival within Spillbay 5 were more pronounced between depths within total spill of 45 kcfs pattern (spill volume of 4.5 kcfs per spillbay) than at bulk spill pattern (40-91 kcfs, spill volume of 11.9 kcfs per spillbay); survival of fish released 3 ft above the ogee ($\hat{\tau}$ =1.013, SE=0.014) was significantly higher (P<0.05) than those released 8 ft above the ogee ($\hat{\tau}$ =0.937, SE=0.020). This finding is contrary to expectation; it was hypothesized that fish released nearer to the ogee would have lower survival because of the potential of colliding with hard structures. Little differences in survival occurred at bulk spill (40-91 kcfs); estimates were within 0.015 of each other (1.5%). The precision (ε) on all estimates was ≤ ± 0.032, 90% of the time.

A regression analysis between survival estimates and measured variables did not reveal a significant correlation (P>0.05) either for Spillbay 1 and 5 in the 2004 investigation or the combined 2003 and 2004 data for Spillbay 5.

Clean fish estimates (fish free of any scale loss, loss of equilibrium, or visible injuries) varied between spillbays, spill volumes, spill patterns, and entrainment depths. At low Tailwater elevation in March 2004, clean fish estimates showed a positive trend with increased spill for fish released at 8 ft above the ogee in both spillbays. The lowest clean fish estimate (0.934, SE=0.025) occurred for fish released at the lowest spill volume (3.4 kcfs) in Spillbay 1; it was 0.953 (SE=0.022) in Spillbay 5 at the lowest spill volume. At high Tailwater elevation in May 2004, except for shallow released fish (20 ft above the ogee and total spill of 45 kcfs), clean fish estimates ranged from 0.876 (SE=0.021) to 0.908 (SE=0.018). The exception (0.963, SE=0.012) was for fish entrained at 20 ft above the ogee at bulk spill with 11.9 kcfs through Spillbay 5 (only spillbay tested in May).

Contrary to non significant relationships for survival estimates some significant correlations were obtained between clean fish estimates and measured variables. For the 2004 data, significant correlation (r =0.608, df =48, P<0.05) was obtained between clean fish estimate and entrainment depth and it approached significance at P=0.05 (calculated r =0.52, tabled r =0.576, df =10) with spill

volume in Spillbay 1. For the combined 2003 and 2004 data at Spillbay 5, significant correlations ($P<0.01$) were obtained between clean fish estimates and entrainment depths and spill volume. Clean fish estimates were not correlated ($P>0.05$) with forebay elevation or tailrace elevations.

The most common injury types observed were hemorrhaged or damaged eyes; these injuries were not lethal, however, over the 48 h observation period. A likely injury mechanism was shear; bruises to the head and body were most likely caused by contacts with spillbay surfaces or stilling basin structures.

In summary, results indicate that fish are more likely to be injured if they pass under the tainter gate close to the ogee, particularly at lower spill volume. It is hypothesized that the smaller tainter gate opening distributes fish closer to the ogee and thereby placing the entrained fish in the vicinity of the flow deflectors. Based on characteristics of injury types observed on entrained fish and sensor fish releases, the immediate area near the flow deflectors appears to be least benign particularly at low spill volume (<5 kcfs). Post-passage condition of fish appear to be better at spill volume >5 kcfs and for fish in the upper water column (> 7ft above the ogee). This finding has practical implications in designing RSW at the Ice Harbor Dam spillway; consideration should be given to spill volume, depth that emigrating fish pass over the RSW and flow deflector depth and shape. If fish pass close to the bottom of the RSW a high potential for injury exits.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX TABLES

1.0 INTRODUCTION

Juvenile salmonids on their seaward journey encounter any or all of the following exit routes at hydro dams: turbines, spillways, and bypasses. There are two inter-related concerns associated with passage through any of these routes for overall survival. One is the proportion of fish utilizing any of these routes during emigration and the other is their subsequent post-passage condition and survival. Spill of varying magnitude and duration is used at most hydro dams on the Columbia River Basin to enhance passage effectiveness and overall survival of juvenile salmonids (Wilson *et al.* 1991). However, spill is expensive in terms of lost power generation and with some spillway configurations and flow patterns, potentially lethal levels of total dissolved gas (TDG) in the river can result. To alleviate the TDG super saturation levels at Ice Harbor Dam on the lower Snake River (Figure 1-1) flow deflectors were installed downstream of Spillbays 1 through 10. Flow deflectors are concrete sills installed on the downstream face of a spillway to maximize the surface skimming effect of spilled water and prevent plunging to the bottom of the stilling basin thus reducing the pressure gradient that forces atmospheric gases into the solution; the installation depths of the flow deflectors varies with sites. As example, flow deflectors downstream of Spillbays 2 through 9 at Ice Harbor Dam are installed approximately 4 ft higher than those at Spillbays 1 and 10 and consequently may produce differential effects on fish condition, TDG, or both. Due to a variety of factors (*e.g.*, spill volume, spill pattern, entrainment depth within a spillbay, and flow deflector elevation), direct survival and injury rates through spillbays equipped with flow deflectors have not been consistently 98% nor have injury rates been ≤ 5% at all of the hydroelectric dams on the Columbia River Basin (Normandeau Associates *et al.* 2003a).

Surface oriented juvenile emigrating salmonids generally occupy the top 20 ft of the water column and must sound to deeper depths to exit via spillways equipped with bottom opening tainter gates at many hydroelectric dams. Depending upon the prevailing water requirements for fish passage or powerhouse discharge, the height of spillbay tainter gates can be adjusted. Thus, the emigrating juvenile salmonids may pass spillbays at different depths relative to tailrace elevation and subject them to varying downstream hydraulic conditions and associated solid objects (*e.g.*, flow deflectors, rock outcrops, etc.) and perhaps resulting in variable survival and injury rates. Table 1-1 provides a range of survival rates estimated for juvenile salmonids in passage through various spillbays at Ice Harbor Dam spillway at different spill volumes. Normandeau Associates (2004) reported that fish released about 3 ft above the ogee of Spillbay 5 suffered a higher injury rate than those released in the upper water column (about 7 ft above the ogee). Injury rates were also lower for fish entrained in Spillbay 5 with a higher spill volume (8.5 kcfs) than at lower spill volume (<5 kcfs). It was hypothesized that a combination of specific Tailwater elevation, submergence depth of the flow deflector, and low spill volume from the tested spillbay may have created a "skim" flow condition at deflectors which could be the source of lower fish survival and higher injury rates. Further, it was thought that at higher Tailwater elevations and higher spill volumes from a spillbay, fish survival and condition could be improved. Figure 1-2 shows a schematic of zones of potential fish injury in passage through the Ice Harbor Dam spillway.

Consequently, the primary objective of the study was to obtain estimates of direct spillway passage survival probability of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, within ±0.03, 90% of the time, at different spill volumes (3.4 kcfs, 5.1 kcfs and 11.9 kcfs) and entrainment depths (3 ft and 8 ft, deep and 20 ft shallow above the ogee). The fish releases were made in Spillbays 1 and 5 in March 2004 low Tailwater and only Spillbay 5 in May 2004 at high Tailwater conditions. The entrainment depths (8 ft and 20 ft above the ogee) (March) selected for the March releases were based on a hydroacoustic investigation, which indicated that most emigrants pass the Ice Harbor spillbays at these depths with spill volume near 5 and 11 kcfs. Additionally, at Spillbay 5 the effects of two spill patterns (total spill of 45 kcfs and bulk spill, 40 to 91 kcfs) were assessed for fish entrained at 3 ft (in May only), 8 ft, and 20 ft above ogee. Spill volume through Spillbay 5 was 4.3 kcfs at the total spill of 45 kcfs when fish were released 3 and 8 ft above the ogee. During the bulk spill when fish were released 3 and 20 ft above the ogee, spill volume through Spillbay 5 was 11.9kcfs.

An additional objective of the investigation was to evaluate the extent and types of injury and likely areas of injury downstream of the spillbays.

As the investigation progressed, it became evident that the above stated objectives could be fulfilled with fewer than the pre-allocated fish for the study; thus, it was deemed prudent to assess some additional operating conditions of potential interest using the remainder of the fish. The additional treatment conditions included releasing fish in Spillbays 1 and 5 at 3.4 kcfs and 11.9 kcfs "replicating" the 2003 experiment at Spillbay 5 thereby assessing the extent of repeatability of the results.

1.1 Project Description

Ice Harbor is the first dam on the Snake River upstream of the confluence with the Columbia River (Figure 1-1). It has six Kaplan type turbine units and 10 spillway bays, along with a navigation lock and an earth fill section. The stilling basin for the spillway is 59 ft long and 168 ft wide with a floor elevation of 304 ft msl. Each spillbay is equipped with a 53 ft high and 50 ft wide tainter gate that seals at an elevation of 389 ft msl. The crest elevation for the spillway is 391 ft msl. Standard-length submersible traveling screens (STSs) are present in all turbine intake bays. The present investigation was conducted at Spillbays 1 and 5 (Figure 1-1).

In order to reduce the level of TDG super saturation produced by water passing over a spillbay, the Corps had installed flow deflectors on the downstream face of all spillbays that direct the flow along the surface of the tailrace rather than allowing it to plunge to the bottom of the spilling basin; these flow deflectors are located at an elevation of 338 ft msl on Spillbays 2 through 9 and at an elevation of 334 ft msl at the outer spillbays (1 and 10). The shallow and deeper flow deflectors are submerged 7 and 11 ft, respectively, below a typical springtime Tailwater elevation of 345 ft msl (Figures 1-3 and 1-4).

A 12 ft high concrete end sill and 8 ft high by 10 ft wide dentate extends across the spillway to aid in energy dissipation (Figure 1-3). These structures are submerged approximately 29 and 33 ft during the typical springtime Tailwater elevation (345 ft msl). The end sill and dentate are approximately 170 and 128 ft downstream of the face of the spillway, respectively.

The Ice Harbor Tailwater elevation is directly dependent upon river flow. At low river flow (less than 50 kcfs), the Tailwater is generally below 341 ft and generally above 345 ft at river flow greater than 100 kcfs. The normal operating range of the tailrace elevation is 339.5 to 345 ft.

In March (low Tailwater elevation), daily Tailwater elevation ranged from 339.1 to 346.2 ft msl (Table 1-1). Thus, the submergence depth of the flow deflectors ranged from about 7.0 to 12.2 ft in Spillbay 1 and 1.1 to 6.8 ft in Spillbay 5. In May (high Tailwater elevation), Tailwater elevation ranged from 341.4 to 346.3 ft (Table 1-1). The submergence depth of the Spillbay 5 flow deflector ranged from 3.4 to 8.3 ft in May (Table 1-1). Spill volume from the tested spillbays was equal to that prespecified in the study plan and remained so during fish releases.

Forebay elevations were similar for the two test periods and ranged from 436.7 to 439.9 ft in March and 438.1 to 439.0 ft in May (Table 1-1). The respective net head values were 92.5 to 99.8 ft and 91.9 to 97.8 ft.

2.0 STUDY DESIGN

Although the study was designed to evaluate the trends in fish passage survival and condition at two spillbays at different spill volumes, all treatments were not duplicated in March and May and thus the results are not directly comparable between the two release sets. The primary emphasis was to obtain precise estimates of direct passage survival through each spillbay although fish releases were made at multiple locations within each spillbay (primarily vertically) to evaluate trends, not to detect statistical differences *per se*. Consequently, statistical tests to detect differences between any two survival or clean fish (fish free of passage related injuries, scale loss or loss of equilibrium) estimates could be made only *a posteriori* to examine trends and use the resulting information for future investigations. A common control was paired with two treatment releases. This scheme has proven efficient in earlier studies and minimizes the use of scarce resources without sacrificing precision ( ) and reduces the duration of an experiment (Mathur *et al.* 1999). A similar study design was employed for an earlier 2003 spillway passage survival experiment at the Ice Harbor Dam (Normandeau Associates 2004).

There are two primary components which affect fish using any exit route: direct and indirect effects. Direct effects are manifested immediately after passage (*e.g.*, instantaneous fish mortality, injury, loss of equilibrium); indirect effects (*e.g.*, predation, disease, physiological stress) may occur over an extended period or distance after passage. The present study was designed to estimate the direct effects. Spillway fish passage survival and condition was estimated by introducing a known number of HI-Z tagged (Heisey et al. 1992) alive fish into Spillbays 1 and 5 (treatment) and control fish released into the fish bypass pipe, recapturing them immediately after passage, enumerating the alive and dead fish, and then carefully examining the condition of each fish. The sample sizes needed to estimate survival within a prespecified precision ( ) level were based on estimating the direct effects of passage through each spillbay at specific volumes. Table 2-1 shows the daily fish release schedule for March and May 2004.

Treatment fish for the primary objectives in March were released at 5.1 kcfs and 11.9 kcfs spill volume, (3 or 7 stops tainter gate openings), 8 ft and 20 ft respectively, above the ogee and approximately 16 ft upstream of the tainter gate in both Spillbays 1 and 5 (Figure 2-1). These two entrainment depths were selected to coincide with where most emigrating smolts were expected to approach the 3 or 7 foot Tailwater gate opening. During tests in March the designated spill volume was discharged primarily from the two test bays (1 or 5) when the fish were released. After a group of approximately 10 – 15 fish were released the test bays was put on seal to facilitate fish recapture and to minimize spill duration. As in 2003 (Normandeau Associates 2004) controls were released via the juvenile fish bypass pipe to assess the effects of handling, transport, tagging, release, and recapture (Figure 1-1). Upon fulfilling the prespecified statistical requirements for the primary objective, secondary releases were made to assess fish condition at other spill volumes of interest in March. This involved fish releases through Spillbays 1 and 5 with the tainter gate openings at 2 stops (3.4 kcfs) and 7 stops (11.9 kcfs) at an entrainment depth of 8 ft above the ogee (Normandeau Associates 2004).

As stated earlier only Spillbay 5 was tested in May. Spill was not confined primarily to the test spillbays in May nor was spill curtailed at any time. Treatment fish were released at three depths (3 ft, 8 ft , and 20 ft above the ogee) and at two different flows (3.4 kcfs and 11.9 kcfs).

2.1 Sample Size Calculations

Prior to initiating the fish survival investigation at Ice Harbor Dam, the sample size requirement was determined to fulfill the primary objective of the study: achieving a precision ( ) level within 0.03, 90% of the time) on the individual estimates of spillbay passage survival ($\hat{\tau}$). The sample size is a function of the recapture rate (P_A), expected passage survival ($\hat{\tau}$) or mortality ($1-\hat{\tau}$), survival of control fish (S), and the desired precision ( ) at a given probability of significance ( ). In general, sample size requirements decrease with an increase in control survival and recapture rates (Figure 2-3). Only precision ( ) and levels can be strictly controlled by an investigator. The expression to calculate sample sizes for achieving a prespecified precision ( ) level is given in Mathur *et al.* (1996).

In performing the sample size calculations, we assumed capture data from replicate releases could be pooled (*i.e.*, natural variability $\sigma_{\tau}^{2} = 0$). We calculated that with the following assumptions: a recapture rate of 0.98, control survival rate (S) of 0.99, and spillbay survival ($\hat{\tau}$) of 0.97, a precision ( ) level of 0.03, 90% of the time might be achievable with releasing 264 fish per treatment; however, only 95 fish per treatment are needed to achieve a precision ( ) level of 0.05, 90% of the time (Table 2-2).

Based on the results of several recent spillbay survival experiments from other sites on the Columbia River Basin (Appendix Table A-1) and the Ice Harbor Dam (Table 2-3), a sample size of approximately 200 and 250 fish per spillbay was deemed sufficient to attain the prespecified precision levels ( ) of +0.03, 90% of the time on resulting survival probabilities.

Although survival and clean fish estimates along with their associated precision ( ) levels for fish released through each release pipe were generated, they were used only to examine trends. As stated earlier, the primary emphasis was to release an adequate number of fish such that the resulting survival estimates of entrained fish through each spillbay at specific spill volumes (primary objective) would be within the prespecified precision ( ) criterion.

Given the above assumptions, the projected number of fish allocated (Table 2-2) for the March releases was 1,800 (1,200 treatment and 600 controls). A similar number of treatment fish (1,200) was allocated in May with 300 control fish. Fewer control fish were needed because only Spillbay 5 was tested. Past experience suggests that the pre-selected sample sizes can be adjusted as a study progresses because the statistical results are available daily. If recapture and control survival rates are higher than initially assumed, sample size can be reduced. Conversely, if the values of these parameters are lower than initially assumed, then sample size can be increased to achieve the pre-specified statistical precision. However, under certain extenuating circumstances (*e.g.*, time, fish availability, or desired test condition constraints) sample size adjustments may not always be possible during the course of an experiment. In the present case, as the study progressed it became evident that less than the entire fish allocation would not be needed to fulfill the requirements set forth for the primary objective. This allowed an opportunity to assess additional spill volumes of interest in March. Thus, fish were released under two additional spill volumes (11.9k and 3.4 kcfs) within each spillbay through the deeper pipe located 8 ft above the ogee.

Appendix B provides statistical, derivations of precision and sample size requirements.

2.2 Source and Maintenance of Specimens

Chinook salmon smolts were obtained from the Leavenworth National Fish Hatchery, Washington. Some 4,500 fish were transported from the hatchery via truck to a 600 gal circular holding pool at Ice Harbor Dam. The transport tank was equipped with a recirculation system and supplemental oxygen supply and could transport about 1,000 fish per trip. The approximate transport time from Leavenworth Hatchery to the study site was 3.5 h. Approximately 24 h prior to tagging, 150 fish were transferred to a 200 gal holding tank on the lower deck, in March and upper spillway deck, in May (Normandeau Associates 2004). Fish holding tanks, equipped with degassing units, were continuously supplied with ambient river water. Fish were held a minimum of 24 h prior to tagging to alleviate handling stress and to allow fish to acclimate to ambient river conditions. Water temperature in the holding pools ranged from 6.0 to 7.5°C (42.8 to 45.5°F) in March and from 12.5 to 14°C (54.5 to 57.2°F) in May.

Fish lengths for the treatment and control fish groups were virtually identical within each release set (Figure 2-4). Lengths of both the treatment and control groups averaged about 135 mm (range 115 to 195 mm) in March and about 150 mm (range 123 to 199 mm) in May.

2.3 Tagging and Release

Fish handling and tagging recapture techniques were identical to those previously used at other hydroelectric projects on the Columbia River Basin, including the Ice Harbor Dam (Heisey *et al.* 1992; Normandeau Associates *et al.* 1996a,b,c; Normandeau Associates 2004). Briefly, lots of 5 to 10 fish were removed with a water sanctuary equipped net from holding tanks (on the spillway deck) to the adjacent tagging site using a small tub full of water. Fish displaying abnormal behavior, severe injury, fungal infection, or descaling (>20% per side) were not used. The same fish selection criterion was applied to all treatment and control groups. Fish were anesthetized in a 0.5% MS 222 solution (<5 min) and equipped with two uninflated HI-Z tags and a miniature radio tag.

Balloon tags were attached via a stainless steel pin inserted through the musculature beneath the dorsal and adipose fins. A radio tag was attached in combination with the dorsal HI-Z tag (Heisey *et al.* 1992). A uniquely numbered VI tag (Visual Implant, Northwest Marine Technology, Inc., Shaw Island, Washington) was also inserted in the post ocular tissue for use in tracking 48 h survival of individual recaptured fish. Fish also received a fin clip to designate release location (test or control) in the event the VI tag became dislodged. HI-Z tagged fish were placed in a covered, 20 gal containers continually supplied with ambient river water until fully recovered from anesthesia (generally 30 to 45 min, minimum 20 min). After full recovery from anesthesia, fish were individually placed into the induction system, tags were activated, and the fish was released. Inflation time of the tags was partially regulated by the temperature and amount of water injected into the tags just prior to release and/or the ingredients within the tag.

All treatment and control fish were released through an induction apparatus (Normandeau Associates 2004) that consisted of a small holding basin attached to a 4 in diameter flexible hose. This induction apparatus was identical to that utilized in the 2003 study at Ice Harbor Dam. The release hose was continuously supplied with river water to ensure fish were transported quickly to the desired release point. The same induction system was used to release the autonomous sensor fish.

At each treatment release site the 4 in diameter flexible hose was threaded through a 6 in diameter welded steel pipe. The steel pipe and hose was held in position by braces mounted on the spillway headwork's and steel guide wires secured to the spillbay nose piers. The terminus of each treatment release hose was oriented downstream either 8 ft (deep) or 20 (shallow) ft above the ogee, in March and May (Figures 2-1 and 2-2). In May fish were also released through a deeper pipe 3 ft above the ogee. In 2003, fish were released 3 ft or 7 ft above the ogee. All release pipes were near the middle of each spillbay and the terminus of the two pipes that were 8 ft and 20 ft above the ogee were approximately 6 ft upstream of the tainter gate, while the deepest pipe (3 ft above ogee) was approximately 16 ft upstream of the tainter gate. The terminus of the 8 ft and 20 ft pipes were positioned based on hydroacoustic fish passage data (Figure 2-1).

Control releases were made into the juvenile fish facility bypass pipe (Figure 1-1). Fish were introduced 1,150 ft upstream of the end of the bypass pipe. The bypass pipe control release site was chosen because dye releases through the Ice Harbor model at the Corps' Vicksburg, Mississippi facility indicated the potential for some fish released downstream of Spillbay 1 to be drawn upstream.

Procedures for handling, tagging, release, and recapture of fish were identical for treatment and control groups. Fish were randomly selected from each day's transport. All fish releases were made during daylight hours (0700 to 1800 h). The spill pattern, however, differed between March and May fish releases. In March, after a group of 10 to 15 tagged fish were released, spill was stopped to conserve water and increase recapture efficiency. The spill was then resumed for the release of the next group of 10-15 treatment fish. Spill remained continuous in May during all fish release-recaptures. Daily hydraulic and physical conditions during testing in March and May 2004 are presented in Appendix Tables C-1 to C-3.

2.4 Fish Recapture

Upon passage, fish were tracked and retrieved when buoyed to the surface downstream of the spillbays by one of three or four recapture boat crews. Boat crews were notified of the radio tag frequency of each fish upon its release. Only crew members trained in fish handling were used to retrieve tagged fish. To minimize crew bias, no crew was specifically assigned to retrieve either control or treatment fish.

Radio signals were received on a 5-element Yagi antenna coupled to an Advanced Telemetry System receiver. The radio signal transmission enabled the boat crew(s) to follow the movement of each fish after passage and position the boats downstream for retrieval when the HI-Z tag buoyed the fish to the surface. Boats were required to remain a safe distance downstream of the turbulent discharge.

Fish that remained in turbulent eddies and could not be safely recaptured were replaced with additional fish. Active radio tags which failed to surface were tracked for a minimum of 30 min and then periodically thereafter to ascertain if fish displayed movement patterns typical of emigrating smolts or that of a predator. Recaptured fish were placed into an on-board holding facility and tags were removed (Heisey *et al.*1992). Each fish was immediately examined for maladies consisting of injuries, descaling, and loss of equilibrium and assigned appropriate condition codes, per the descriptions presented in Table 2-4. Tagging and data recording personnel were notified via a two-way radio system of each fish's recovery time and condition.

Each recaptured fish with a visible injury or scale loss was assigned a likely causal mechanism. Limited controlled laboratory experiments (Neitzel *et al.* 2000; PNNL *et al.* 2001) to replicate and correlate injury type and characteristic to a specific causative mechanism provides some indication of the cause of observed injuries in the field. Some injury symptoms can be manifested by two different sources which may lessen the probability of accurate delineation of a cause (Eicher Associates 1987).

All fish recaptured alive were transferred in 5 gal pails to 600 gal pools on the lower deck (March) and the upper spillway deck (May) for assessment of delayed effects (48 h). Each pool, equipped with a degassing unit, was continuously supplied with ambient river water and shielded to prevent potential fish escape and/or avian predation. Each day's treatment and control fish were held together in the same pools for 48 h.

2.5 Classification of Recaptured Fish

As in previous investigations on the Columbia River Basin, including Ice Harbor Dam (Normandeau Associates *et al.* 1996a,b,c, 1997; Normandeau Associates and Skalski 1998, 1999, 2000a,b,c; Normandeau Associates 2004) the immediate post-passage status of an individual recaptured fish and recovery of inflated tags dislodged from fish was designated as alive, dead, tag and pin recovered, unknown, or predation. The following criteria have been established to make these designations: (1) alive--recaptured alive and remaining so for 1 h; (2) alive--fish does not surface but radio signals indicate movement patterns typical of emigrating juveniles; (3) dead--recaptured dead or dead within 1 h of release; (4) dead--only inflated dislodged tag(s) are recovered, and telemetric tracking or the manner in which inflated tags surfaced is not indicative of predation; (5) unknown--no fish or dislodged tags are recaptured, or radio signals are received only briefly, and the subsequent status cannot be ascertained; and (6) predation--fish are either observed being preyed upon, the predator is buoyed to the surface, or subsequent radio telemetric tracking indicates predation (*i.e.*, rapid movements of tagged fish in and out of turbulent waters or sudden appearance of fully inflated tags). Unrecovered preyed upon fish are assumed dead in the survival calculations; alive recaptured fish suspected of predator attack were included with the alive category.

Mortalities of recaptured fish occurring after 1 h were assigned 48 h post-passage effects although fish were observed at approximately 12 h intervals. Specimens were examined for descaling and injury, and those that died were necropsied to determine the probable cause of death. Additionally all specimens alive at 48 h were re-anesthetized and closely examined for injury and descaling. The re-examination of immobilized fish minimizes the need for extensive handling and associated stress upon immediate recapture. The initial examination allows detection of some injuries, such as bleeding and minor bruising that may not be evident after 48 h due to natural healing processes (Normandeau Associates *et al.* 1996a,b,c). Injury and descaling were categorized by type, extent, and area of body.

Fish without visible injuries that were not actively swimming or swimming erratically at recapture were classified as “loss of equilibrium”. This condition has been noted in most past studies and often disappears within 10 to 15 min after recapture if the fish is not injured (Normandeau Associates *et al.* 1996a,b,and c). A malady category was established to include fish with visible injuries, scale loss (greater than 20% on either side), or loss of equilibrium. Dead fish without any of these symptoms were not included in this category. Fish without maladies were designated “clean fish”. Detailed descriptions of maladies observed on each recaptured fish are presented in Appendix Tables D-1 and D-2.

The clean fish metric was established to provide a standard way to depict a specific passage route’s effects on the condition of entrained fish (Normandeau Associates *et al.* 2003a,b). The clean fish metric is based solely on fish physically recaptured and examined. Additionally, the clean fish metric in concert with site-specific hydraulic and physical data may provide insight into what passage conditions present safer fish passage.

2.6 Spill Volume and Impact Velocity

Impact velocities were estimated for the various spillbay gate openings tested for deflector impact only because the discharge flow swept the deflector. The velocity of the discharge jet upon impact with the flow deflector was calculated by adding vertical and horizontal vectors of velocity (Mr. Duncan Hay, personal communication). The vertical component was calculated based on the vertical distance from the center of the jet to the deflector. The estimated impact velocities were in the range of 70 to 73 ft/s; the laboratory studies suggest these velocities exceed those capable of inflicting injury/mortality (approximately 58 ft/s) on fish (Neitzel *et al.* 2000).

2.6.1 Tailwater Flow Characteristics

Depending upon the Tailwater elevations the spill volumes and spill patterns affect the flow characteristics with their unique potential influences on the condition of entrained fish. Based on model studies of flow deflectors and depending upon the action in the spilling basins, Wilhems *et al.* (2003) identified several primary hydraulic conditions in the stilling basin: plunging flow, unstable or surging flow, skimming flow, undulating flow or an undulating surface jet, ramped surface jet, surface jump, and submerged surface jump. Examples of these flow conditions are reproduced in Figure 2-5. From the standpoint of total dissolved gas abatement skimming flow was deemed desirable; however, its potential effects on post-passage fish condition are unknown.

2.7 Survival and Clean Fish Estimation and Data Analysis

Passage survival probabilities ($\hat{\tau}$) for each treatment were estimated relative to the control fish survival (Heisey *et al.* 2002a; Mathur *et al.* 1996, 1999). Data from individual daily trials (Appendix Tables D-1 and D-2) were used in the analysis. Two treatment and one common control conditions were simultaneously analyzed and modeled by joint likelihood (Normandeau Associates 2004).

A likelihood ratio test was used to determine whether recapture probabilities were similar for alive (P_A) and dead (P_D) fish. The statistic tested the null hypothesis of the simplified model (H_o:P_A=P_D) versus the alternative of the generalized model (H_A:P_A P_D). Depending upon the outcome of this analysis for the 1 h survival the parameters and their associated standard errors were calculated using that model for the 48h estimation as well. However, outputs of reduced model are used for the clean fish estimate metric because it was based only on recaptured fish in hand (Normandeau Associates 2004).

As in previous studies (Normandeau Associates and Skalski 2000a), separate chi-square analyses were performed to test for homogeneity (P=0.05) between daily treatment and control releases with respect to recapture frequencies of alive, dead, and non-recovered fish; contingency tests allow for checking for homogeneity and suggest subsets of data to be pooled in the final estimation (Burnham *et al.* 1987). For example, if homogeneity between daily control releases is detected (P>0.05) then the release data can be pooled and survival for each treatment estimated relative to survival of the pooled control group. Likewise homogeneity (P>0.05) between daily trials for each treatment would allow pooling of all daily trials data within each treatment.

The clean fish estimate (CFE) was also calculated for each treatment condition (Normandeau Associates 2004). As stated earlier, it was based on recaptured fish without maladies (*i.e.*, no visible injuries, scale loss, or loss of equilibrium) or displayed maladies that were not attributable to passage, *i.e.*, injuries attributed to predator attack or tag induced (tear at tag site). Only recaptured fish that were visibly examined were included in the clean fish estimation analysis. Clean fish estimates were made relative to the control fish without maladies. Data from individual daily trials (Appendix Tables D-5 and D-6) were used in this analysis.

The 90% confidence intervals on the survival or clean fish estimates were calculated using the profile likelihood method (Normandeau Associates 2004); these are deemed superior to those based on the assumption of normality. Although the study was not designed for hypothesis testing, differences in survival and clean fish estimates between spill rates or passage location were tested *a posteriori* by Z-statistic to examine trends. These comparisons were not hypothesis based. As indicated earlier, sample sizes for the study were selected to achieve a pre-specified precision ( ) on survival estimate for each spillbay at a given probability level and not for each treatment condition tested after the primary objective was fulfilled. Also, it should be noted that because of the multiple comparisons the probability level (P=0.05) may not be deemed exact.

Relationships between clean fish metric and measured hydraulic variables (*e.g.*, spill volume, river flow, Tailwater elevation, etc.) were examined via regression analysis. Both linear and nonlinear regression analyses were conducted to select the best predictive model. A General Linear Model, (GLM), procedure was used to evaluate the variation in clean fish and survival estimates attributable to spill volume, spillbay, and interaction of spill volume and spillbay. Because of relatively larger sample size of daily estimates of survival and clean fish for fish released 8 ft above the ogee at the three spill volumes analyses was performed using these data. Data used in regression analyses are given in Appendix Table D-7. Additionally, statistical analysis was performed including all daily estimates for both 2003 and 2004 to examine trends in clean fish or survival as a function of spill volume, entrainment depth, forebay elevation, and Tailwater elevation.

All statistical analyses were conducted using the Statistical Analysis System (SAS). The statistical outputs with exact probabilities are provided in Appendix D (output discussed in the report is highlighted).

The disposition of individual fish is given in Appendix E and only summarized information is discussed in the main body of the report.

2.8 Autonomous Sensor Fish

Sensor fish, an instrumented package designed to determine exposure histories to turbulence and pressure during passage (PNNL *et al.* 2001) were equipped with two or three HI-Z tags and a miniature radio tag and released using the identical induction release hose into the same spill conditions as for the alive fish experiment. Sensor fish were also released at the control site. Generally, at least one sensor fish was released with each group of 10 fish. The results of sensor fish passage are to be provided by PNNL in a separate report.

3.0 RESULTS

3.1 Recapture Rates

Recapture rates (physical retrieval of both alive and dead fish) of treatment and control groups were high (Tables 3-1to 3-3). Recapture rates of treatment groups exceeded 95% for all conditions. Recapture rates of the control group were also high (≥96%). Almost all of the recaptured treatment fish were alive. However, some predation (up to 2%) was suspected on fish released in May (Table 3-3).

Chi-square analyses indicated homogeneity (P>0.05) between daily control trials, allowing for the pooling of data. Homogeneity (P>0.05) was also revealed between daily trials of each treatment group. Thus, survival for each treatment was estimated relative to survival of the pooled control trials (Normandeau Associates *et al.* 2003a, b).

The likelihood ratio test indicated no significant difference (P>0.05) between the simplified and generalized models. Thus, survival probabilities and their associated standard errors were calculated using the simplified model for all treatments.

3.2 Retrieval Times

Retrieval times (the interval between fish release through the induction system and physical retrieval) for various releases were short and generally similar; however, some fish were free for over 100 min. Average times for treatment groups were about 9 min and 6-7 min for controls (Figure 3-1).

3.3 Survival Estimates

The 1 h survival estimates differed somewhat between spillbays, entrainment depth, spill volume, and spill patterns (Table 3-4). The differences were relatively more pronounced at high Tailwater elevation than at low Tailwater elevation. Survival estimates for Spillbays 1 and 5 fish were all ≥0.988 (all standard errors ≤0.01) for the six treatment conditions at low Tailwater elevation. In May (Spillbay 5 only), survival estimates ranged from 0.965 (SE=0.017) to 1.0 (SE=0.014). The lowest survival (0.965, SE=0.017)) was for fish released 3 ft above the ogee with 11.9 kcfs passing Spillbay 5 with a total spill of 40–91 kcfs (bulk spill). The highest survival (1.0, SE=0.014) in May also occurred for fish released 3 ft above the ogee but at the lower spill volume of 4.3 kcfs and total spill of 45 kcfs(Table 3-4).

The 48 h survival rates exhibited a similar trend (Table 3-4). Little additional mortality occurred over the 48 h for March released fish, the 48 h survival for the six treatments ranged from 0.979 to 0.997 (all standard errors ≤0.014). However, in May additional mortality occurred, particularly for fish released at 8 ft above the ogee with spill volume of 4.3 kcfs and total spill of 45 kcfs; survival decreased from 0.979 (SE=0.016) at 1 h to 0.937 (SE=0.020) at 48 h.

The effect of spill volume and entrainment depth on 48 h survival was not consistent in May. The lowest 48 h survival (0.937) occurred at the same spill conditions, but fish were entrained 8 ft above the ogee. The highest survival (1.0) also occurred for fish released at 3 ft above the ogee with 4.3 kcfs passing and total spill of 45 kcfs. The 48 h survival estimates for the remaining two treatment conditions (3 ft and 20 ft above the ogee fish releases) at spill volume of 11.9 kcfs (bulk spill of 41-91 kcfs) were intermediate (0.950 and 0.965) to the above two estimates. The prespecified precision (ε) level of $\leq +0.03$, 90% of the time, was met on all survival estimates except one (45 kcfs spill, 8 ft above ogee) in May (Table 3-4). Although the original study design did not require an assessment of survival for deep released fish in both Spillbays at 3.4 and 11.9 kcfs in March 2004 (Table 3-2) the recapture of virtually all fish released allowed reliable survival estimates for these treatments as well; they were all $\geq$0.98 with precision (ε) of $\leq$ 0.02, 90% of the time (Table 3-4).

Two linear regression analyses of the 48 h survival estimates were conducted; one using the 2004 data alone and the second including the 2003 data. For the 2004 daily survival estimates, no significant ($P>0.10$) correlations were found between survival, and spill volume, forebay elevation, tailrace elevation, or entrainment depth in either spillbay (Figure 3-2). Figure 3-3 shows the same relationships including the 2003 data. No signification correlations ($P > 0.10$) between survival rate and any other variable tested were observed for these data as well.

Table 3-5 summarizes survival point estimates from Spillbay 5 in 2003 and 2004 as a function of spill volume and entrainment depth. At spill volume of >5 kcfs and entrainment depth $\geq$7 ft survival was generally $\geq$0.98.

3.4 Injury Rates and Probable Causal Mechanisms

All recaptured fish, dead or alive, were examined for types of external injuries. Dead fish were also examined for internal injuries. Injuries rates given below are based on the total number of fish recaptured and examined, not on the total number of fish released and refer to only passage-related injuries. Control fish in the March study did not sustain any visible injuries, thus no adjustments for control injury rates were necessary (Table 3-6). In May, 1 of 292 (0.3%) control fish recaptured sustained visible injuries (Table 3-7). Thus, injury rates for treatment fish were adjusted for control fish injury rates.

Fish injury rates differed between spill volumes, spill patterns, entrainment depths within spillbays, and releases in March and May (Tables 3-6 and 3-7). Injury rates were higher for fish entrained at deeper locations, nearer the ogee, (3 ft to 8 ft above the ogee) and lower spill volume (< 5 kcfs) than for those released at the shallower depth (20 ft above ogee). In March, highest injury rate (6.7%) was for fish released 8 ft above the ogee of Spillbay 1 at a low spill volume of 3.4 kcfs; minimal injury ($\leq$ 1%) was observed for three of the four high spill volumes (11.9 kcfs) tested. The exception (2.5%) being at Spillbay 5 for fish released 8 ft above the ogee at spill volume of 11.9 kcfs. However, the sample size was deemed too small (40 fish released and examined) to be reliable (Table 3-6).

Overall injury rates in March were slightly higher on fish entrained in Spillbay 5 (2.7%) than in Spillbay 1 (2.2%). Visible injury rate was higher in May (Table 3-7). Injury rates were 8.6-12.7% for three of the four treatments for fish released 3 or 8 ft above the ogee in Spillbay 5 with a spill volume of 4.3 or 11.9 kcfs. The least injury rate (2.3%) was observed for fish released 20 ft above the ogee and at the highest discharge (11.9 kcfs).

The most common injury types observed were hemorrhaged or damaged eyes with a maximum injury rate of 11.3% for fish released 8 ft above the ogee and a spill volume of 4.3 kcfs through Spillbay 5

(Tables 3-6 and 3-7). Overall rate of eye damage in March was 1 and 1.9% for the tests conducted in Spillbays 1 and 5, respectively. In May the overall rate of eye injury for Spillbay 5 tests at 45 kcfs and bulk spill was 7.5 and 3.7%, respectively. Bruises to the head and operculum/gill damage were the next two common injury types. The highest incidence (3.5%) of operculum/gill damage occurred for the fish released at 4.3 kcfs discharge, 8 ft depth in May. The highest incidence (2.9%) of bruising to the head or body also occurred for the same test condition. Shear forces were the most likely cause of hemorrhaged or damaged eyes as well as operculum and gill damage. Physical contact with spillbay surfaces or stilling basin structures was the most likely cause of bruises to the head or body.

Malady rates, with included visible injuries plus loss of equilibrium, and major scale loss did not differ much from injury rates alone because relatively few additional fish incurred only loss of equilibrium or showed scale loss (Tables 3-8 and 3-9). Although the percentage of fish with maladies was as high as 12.3% (3 ft release, 4.5 kcfs spill volume) relatively few of these fish died (Tables 3-8 and 3-9). Nine of 36 (25.0%) and 25 of 117 (21.0%) of the fish with maladies in the March and May releases, respectively, died.

3.5 Clean Fish Estimates (CFE)

Clean fish estimates, complement of malady rates, followed an opposite trend to malady rates (Table 3-10). The effect of spill volume and release depth was more evident on CFE metric than for survival estimates. In both spillbays at low Tailwater elevation, CFE for deep released fish in Spillbay 1 showed a positive trend with increasing spill volume with lower CFE (0.934 to 1.00, model constraints precluded calculation of standard errors) at low spill volumes (3.4 kcfs and 4.3 kcfs). In Spillbay 5, CFE followed the same pattern with 0.953 (SE=0.022) at 3.4 kcfs and 0.977 (SE=0.023) at 11.9 kcfs. In general, fish released closer to the ogee (3 ft) had lower CFE particularly at low spill volume (4.3 kcfs) and high values at the higher spill volumes. The lowest CFE of 0.876 was for fish released closest to the ogee (3 ft) and at the lowest spill volume (4.3 kcfs). CFE for shallow released fish (20 ft above the ogee) at comparable spill volumes was quite high (0.936-0.987) and similar in both spillbays (Table 3-10).

Table 3-11 summarizes the CFE estimates as a function of spill volume and entrainment depth in Spillbay 5 for tests conducted in 2003 and 2004 (only Spillbay 5 tested in both years). The effect of spill volume and entrainment depth is more pronounced in this matrix. CFE estimates were higher for fish entrained higher in water column (≥ 7 ft) regardless of spill volumes. CFE estimates of fish entrained near the ogee (3 ft release) were low (0.793 to 0.899) regardless of spill volume discharged through Spillbay 5, but there was a slight trend toward higher CFE's at higher discharges. The higher CFE's for these two years of testing at Spillbay 5 occurred at 7 ft release with per spillbay spill of 4.3-8.5 kcfs. Total spill of 42-79 kcfs and 20 ft release with per spillbay spill of 11.9 kcfs, total spill of 40-91 kcfs.

Regression analysis of CFE was conducted to quantify the above trends; initially the 2004 daily estimates and then with 2003 data incorporated. Figures 3-4 and 3-5 show the bivariate plots of these relationships for Spillbays 1 and 5. No attempt was made to fit higher degree polynomial to these data.

For the 2004 Spillbay 5 data, clean fish estimate was significantly correlated ($P < 0.01$) with entrainment depth; no other significant relationship ($P>0.05$) was observed. Although the sample size for Spillbay 1 data was small ($N=12$) the correlation ($r = 0.52$) between CFE and spill volume approached significance at $P=0.05$. When the data from 2003 were included with the 2004 Spillbay 5 data significant correlations ($P< 0.05$) between CFE and entrainment depth and spill volume were evident. CFE increased with increased spill volume and shallower entrainment depth (Figure 3-5).

4.0 DISCUSSION

The primary objectives and assumptions established for the experiment were met. Also, the embedded flexibility in the study design allowed evaluation of two additional treatment conditions, *albeit* with smaller sample size. The pre-specified precision ( ) level of ±0.03, 90% of time on survival estimates was achieved with fewer fish than initially allocated in March. The remaining fish were used to assess the potential effects of spill volumes of 3.4 kcfs and 11.9 kcfs at Spillbays 1 and 5 on fish entrained at 8 ft above ogee. This fish release scheme was comparable to that utilized in the 2003 study (Normandeau Associates 2004) and provided an assessment of repeatability of results.

Identifying the specific spill volumes and potential entrainment depths for relatively benign fish passage may provide manager's avenues to enhance survival when considering spill patterns and spillbay modifications for juvenile salmonid passage. The present study succeeded to a large extent in identifying these conditions for spillway passage at Ice Harbor Dam. It had been hypothesized (Normandeau Associates 2004) that fish entrained in upper water column layer (shallow released fish), i.e., exiting farther above the ogee, would traverse a more benign path than those nearer the ogee (deep released fish). Fish condition, as indexed by clean fish estimates, was consistently better (≥0.91) at a combination of spill volume >5 kcfs per spillbay and entrainment depth of ≥7 ft above the ogee. However, some variability does exist and all spillbays may not yield identical results relative to fish condition. The clean fish estimate for fish released 3 ft above the ogee in Spillbay 5 at 11.9 kcfs was significantly less than for fish released 20 ft above the ogee; 0.899 vs. 0.963. However, in Spillbay 1 the clean fish estimates were about the same for fish released 8 ft (CFE 1.00) and 20 ft (CFE 0.987) above the ogee at the high discharge (11.9 kcfs) volume. No fish were released close (3 ft) to the ogee at Spillbay 1. It is likely that all the released fish did not traverse the same path exiting the two spillbays or encountered different "micro-hydraulic" conditions downstream of respective spillbays perhaps in part due to surge flows. The submergence depth of flow deflectors downstream of Spillbay 1 is about 4 ft deeper than for those downstream of Spillbay 5 which may create different hydraulic conditions, particularly at lower spill volume (3.4 kcfs). Additionally, the deepest release location (only 3 ft above the ogee) also inflicts more injury regardless of the discharge rate. The clean fish estimates for five test conditions conducted at Spillbay 5 with discharges ranging from 3.4-11.9 kcfs were all less than 89.9%. Consequently, when designing the removable spillway weir (RSW) for the Ice Harbor Dam consideration should be given to spill volume and the depth at which the bypassed fish will be exiting, and flow deflector depth and shape.

Hydroacoustic data from Ice Harbor Dam spillway study in 2003 (Moursund *et al.* 2003) indicated that the greater the tainter gate opening the higher the fish pass above the ogee. PNNL estimated that approximately 50% of the entrained fish would pass close to 8 ft and 20 ft above the ogee at a tainter gate opening of 3 and 7 ft, respectively. This corresponds to spillbay volume of 5.1 and 11.9 kcfs. Since the present study suggests that fish passing farther above the ogee (shallow released fish) have lesser chance of injury it may be surmised that naturally entrained fish passing higher in the water column may exit a benign path. However, at lower spill volume and tainter gate openings fish may be forced to pass close to the ogee during passage and this may result in injury.

The actual path traversed by each balloon tagged fish released in the present study is unknown. However, data from concurrent release of balloon tagged "sensor fish" by PNNL to characterize and identify the hydraulic conditions experienced by alive released fish indicate potentially less injurious hydraulic conditions higher in the water column. Sensor fish released via the pipe 20 ft above the ogee detected the least turbulent hydraulic conditions downstream, particularly in the immediate vicinity of the flow deflector. Sensor fish released nearer the ogee appeared to experience more turbulent conditions.

Results from the two years of release of alive HI-Z tagged fish (2003 and 2004), when taken together, suggest that survival and condition can be expected to be high for fish exiting the spillbays higher in the water column (20 ft above the ogee) at spill volumes (≥5 kcfs). The shallower entrainment depths appear to place the fish in a more benign egress route and away from potential collisions with solid structures.

One notable finding of the 2004 experiment was repeatability of results, as indexed by survival probabilities, at comparable spill volumes in Spillbay 5. Survival estimates derived in 2003 at spill volumes of 3.4 to 8.5 kcfs ranged from 0.987 to 1.00 (Normandeau Associates 2004). In March 2004, at comparable spill volumes of 3.4 kcfs and 5.1 kcfs estimated survival probabilities were at 0.986 to 0.988.

Different tag-recapture techniques may provide variable survival estimates. The estimated survival rates in the present study were similar those derived from PIT tag and radio telemetry. The preliminary survival estimate from PIT tagged fish released through Spillbays 1 and 3 was 96% (Absolon *et al.* 2003). In the present study, survival estimates ranged from 93.7 to 100%. PIT tagged fish were released at a relatively shallow depth, 10 ft above the ogee, upstream of the tested spillbay (Absolon *et al.* 2003). The higher release point likely allowed most fish to pass under the tainter gate higher in the discharge jet and further away from the ogee. Just considering HI-Z tagged fish released at least 8 ft above the ogee, the present study survival estimates are all ≥96.5%, except for one test condition (93.7%) where fish were released 8 ft above the ogee at a low discharge volume of 4.3 kcfs. It is likely fish passing higher in the discharge jet have a sufficient "water cushion" which minimizes chances of collision with the downstream solid structures and encounter with high shear forces near the periphery of the discharge jet.

The assignment of causal mechanisms to individual injury types in the field though difficult, followed symptoms noted by Neitzel *et al.* (2000) in laboratory studies. They reported that localized shear forces caused a variety of injuries to the eyes, opercula's, and body of juvenile salmonids. In the current study, most of the passage-related eye injuries and tears at the opercula attachment site were attributed to shear forces. However, some of the eye damage may have been due to physical contact with spillway structures, likely the flow deflector. Additionally, tears and abrasions on the opercula appeared to be contact related. Scrapes and swaths of scale loss on the head or body were attributed to contact or impact with the spillbay flow deflector or Tailwater structures (baffles and end sill). Some bruises, however, can be caused by shear forces (Neitzel *et al.* 2000).

Fish condition is poor when a fish strikes a solid object, even at lower velocities, than when they enter standing water without obstructions. A variable mortality rate was observed by Bell *et al.* (1972) when fish struck a solid object at a velocity exceeding 20 fps. No fish injury was observed when fish impacted flowing water at a velocity of about 60 fps. They concluded that fish could be injured in any high-energy flow situation that creates momentarily localized sharp velocity changes. Based on field and laboratory tests little to no fish injury was observed on juvenile salmon subjected to entry velocities as high as 50 fps (PNNL *et al.* 2001). The impact velocity of the discharge jet upon tailrace was estimated to range from 71 to 75 fps during the current investigation. Injury rates were quite variable in the present study and ranged from 0.0 to 12.7%; with the highest incidence of injury (8.9 and 12.7%) for deepest (3 ft release) passed fish. A predictive relationship between the fish condition and impact velocity is difficult to develop from the available field data so a calculation of specific impact velocity threshold tolerance is not possible. Field data were collected over a narrow range of impact velocities and opportunity was not afforded to vary the impact velocity as can be done in a laboratory setting.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Survival rates and fish condition may not be assumed identical in passage through different spillbays. Absolute survival and clean fish probabilities (fish free of passage-related malady) produced somewhat conflicting results between spillbays with respect to the effects of differential spill volume.

The 48h survival rates (ranged from 93.7 to 100%) between spillbays at the three spill volumes (3.4, 5.1, and 11.9 kcfs) and three entrainment depths (3 ft, 8 ft, and 20 ft above the ogee) while differences in clean fish estimates were more pronounced and ranged from 87.6 to 100%. Within Spillbay 1, clean fish estimates appeared positively correlated with increasing spill volume; estimates for deep released fish were highest (1.00) at 11.9 kcfs and lowest (0.944) at 3.4 kcfs. Within Spillbay 5, clean fish estimates varied slightly between spill volumes with the lowest (0.876) occurring at 4.3 kcfs and highest (1.00) at 11.9 kcfs; however if fish passed close to the ogee (3 ft release) the spill volume had much less beneficial effect clean fish estimates were only 0.899 at a spill volume of 11.6 (per bay) when the fish were released 3 ft above the ogee.

In general fish condition improves as spill volume increases and when fish are entrained higher in the water column.

Although potentially injurious impact velocities (>70 ft/s) occurred, based on laboratory tests, post-passage fish condition was generally good except when fish were released within 3 ft of the ogee. Based on two years of testing at Ice Harbor spillbays the high water velocities of the discharge jet appear to have a substantial negative effect primarily when fish pass deep within the jet or near the periphery of the jet.

Most likely fish injury mechanisms were shear and physical contact with spillbay surfaces or stilling basin structures.

When designing a removable spillway weir (RSW) consideration should be given to spill volume, depth that emigrating fish pass over the RSW, and flow deflector depth and shape. If fish pass close to the bottom of the RSW (just above the skin of the weir) there maybe a high potential for fish injury.

6.0 LITERATURE CITED

Absolon, R. F., M. B. Eppard, B. P. Sandford. 2003. Relative survival of PIT tagged hatchery Chinook salmon through Ice Harbor Dam, 2003. U. S. Army Corps of Engineers 2003 Anadromous Fish Evaluation Program (AFEP) Annual Review, Walla Walla, WA.

Bell, M. C., A. C. DeLacy, and H. D Copp. 1972. A compendium on the survival of fish passing through spillways and conduits. Report prepared for U.S. Army Corps of Engineers, Portland, OR.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for survival experiments based on release-recapture. American Fisheries Society, Mongr. 5, Bethesda, MD.

Carlson, T. J., and J. P. Duncan. 2003. Characterization of the Ice Harbor spill environment. U.S. Army Corps of Engineers 2003 Anadromous Fish Evaluation Program (AFEP) Annual Review, Walla Walla, WA.

Eicher Associates, Inc. 1987. Turbine-related fish mortality: review and evaluation of studies. Research Project 2694-4. Prepared for Electric Power Research Institute, Palo Alto, CA.

Eppard, M. B., E. E. Hockersmith, G. A. Axel, and B. P. Sandford. 2003. Migrational behavior and survival of radio tagged hatchery yearling Chinook salmon at Ice Harbor Dam, 2003. U. S. Army Corps of Engineers 2003 Anadromous Fish Evaluation Program (AFEP) Annual Review, Walla Walla, WA.

Heisey, P. G., D. Mathur, and T. Rineer. 1992. A reliable tag-recapture technique for estimating turbine passage survival: application to young-of-the-year American shad (*Alosa sapidissima*). Can. Jour. Fish. Aquat. Sci. 49:1826-1834.

Heisey, P. G., D. Mathur, J. R. Skalski, and R. C. McDonald. 2002a. Effects of spillway structural modifications on juvenile salmonids survival. Amer. Fish. Soc. 4th BioEngg. Symposium, Baltimore, MD. (In review with editor)

Mathur, D., P. G. Heisey, E. T. Euston, J. R. Skalski, and S. Hays. 1996. Turbine passage survival estimation for Chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River. Can. Jour. Fish. Aquat. Sci. 53:542-549.

Mathur, D., P. G. Heisey, J. R. Skalski, and D. R. Kenney. 1999. Survival of Chinook salmon smolts through the surface bypass collector at Lower Granite Dam, Snake River. Pages 119-127 in M. Odeh, editor. Innovations in fish passage technology. American Fisheries Society Bethesda, Maryland.

Moursund, R. A., K. D. Ham, P. S. Titzler, and F. Khan. 2003. Hydroacoustic evaluation of the effects of spill treatments on fish passage at Ice Harbor Dam in 2003. U. S. Army Corps of Engineers 2003 Anadromous Fish Evaluation Program (AFEP) Annual Review, Walla Walla, WA.

Neitzel, D. A., and nine co-authors. 2000. Laboratory studies of the effects of shear on fish, final report FY 1999. Prepared for Advanced Hydropower Turbine System Team, U. S. Department of Energy, Idaho Falls, ID.

Normandeau Associates, Inc. 2004. Juvenile salmonid direct survival/injury in passage through the Ice Harbor Dam spillway, Snake River. Report prepared for Department of the Army, Walla Walla District, Walla Walla, WA.

Normandeau Associates, Inc., and J. R. Skalski. 1998. Chinook salmon smolt passage survival through modified and unmodified spillbays at Rock Island Dam, Columbia River, Washington. Report prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Normandeau Associates, Inc., and J. R. Skalski. 1999. Evaluation of mortality and injury associated with smolt passage through spillbays with a sloped flow deflector and no flow deflector at the Wanapum Dam. Report prepared for the Grant County Public Utility District No. 2, Ephrata, WA.

Normandeau Associates, Inc., and J. R. Skalski. 2000a. 1999 spillway passage survival investigation of juvenile Chinook salmon at Rock Island Dam, Washington. Report prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Normandeau Associates, Inc., and J. R. Skalski. 2000b. Evaluation of prototype shallow-flat deflector at Wanapum Dam spillbay 5 relative to Chinook salmon smolt passage survival, 1999. Report prepared for Grant County Public Utility District No. 2, Ephrata, WA.

Normandeau Associates, Inc., and J. R. Skalski. 2000c. Passage survival investigation of juvenile Chinook salmon through a bypass pipe on the Columbia River, Washington. Report prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Normandeau Associates, Inc. and Mid Columbia Consulting, Inc. 2001. Feasibility of estimating direct mortality and injury on juvenile salmonids passing The Dalles Dam spillway during high discharge. Report prepared for Department of the Army, Corps of Engineers, Portland District, Portland, OR.

Normandeau Associates, Inc. and Mid Columbia Consulting, Inc. 2003. Feasibility of estimating passage survival of adult salmonids using the HI-Z tag-recapture technique. Report prepared for Department of the Army, Walla Walla District, Walla Walla, WA.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 1995. Turbine passage survival of juvenile Chinook salmon (Oncorhynchus tshawytscha) at Lower Granite Dam, Snake River, Washington. Report prepared for U. S. Army Corps of Engineers, Walla Walla, WA.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 1996a. Potential effects of modified spillbays on fish condition and survival at Bonneville Dam, Columbia River. Report prepared for Department of the Army, Portland District COE, Portland, OR.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 1996b. Potential effects of modified spillbays on fish condition and survival at The Dalles Dam, Columbia River. Report prepared for Department of the Army, Portland District COE, Portland, OR.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 1996c. Fish survival in passage through the spillway and sluiceway at Wanapum Dam on the Columbia River, Washington. Report prepared for the Grant County Public Utility District No. 2, Ephrata, WA.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 1997. Juvenile steelhead passage survival through flow deflector spillbays versus a non-flow deflector spillbay at Little Goose Dam, Snake River, Washington. Report prepared for Department of the Army, Walla Walla District COE, Walla Walla, WA.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 2003a. Juvenile salmonid survival and condition in passage through modified spillbays at Bonneville Dam, Columbia River. Report prepared for Department of the Army, Portland District, Portland, OR.

Normandeau Associates, J. R. Skalski, and Mid Columbia Consulting, Inc. 2003b. Estimated direct mortality and injury rates of juvenile salmonids in passage through The Dalles Dam spillway, Columbia River, in spring and summer 2002. Report prepared for Department of the Army, Corps of Engineers, Portland District, Portland, OR.

Pacific Northwest National Laboratory (PNNL), BioAnalysts, ENSR International, Inc., and Normandeau Associates, Inc. 2001. Design guidelines for high flow smolt bypass outfalls: field, laboratory and modeling studies. Report prepared for the U. S. Army Corps of Engineers, Portland District, Portland, OR.

Wilhems, S., P. E. Murphy, Jr., and L. I. Yates. 2003. Ice Harbor spillway hydraulic model study. Report prepared by ERDC Coastal and Hydraulics Lab.

Wilson, J. W., A. E. Giorgi, and L. C. Stuehrenberg. 1991. A method for estimating spill effectiveness for passing juvenile salmon and its application at Lower Granite Dam on the Snake River. Can. J. Fish. Aquat. Sci. 48:1872-1876.

TABLES

FIGURES

APPENDIX A

SURVIVAL ESTIMATES, RECAPTURE, AND CONTROL SURVIVAL RATES FROM THE COLUMBIA RIVER BASIN HYDROELECTRIC DAMS

APPENDIX B

DERIVATION OF PRECISION, SAMPLE SIZE, AND MAXIMUM LIKELIHOOD PARAMETERS AND STATISTICAL OUTPUTS

DERIVATION OF PRECISION, SAMPLE SIZE, AND MAXIMUM LIKELIHOOD PARAMETERS

The statistical description below is excerpted from Normandeau Associates and Skalski (2000a). For the sake of brevity, references within the text have been removed. However, interested readers can look up these citations in the report prepared by Normandeau Associates and Skalski (2000a).

The estimation for the likelihood model parameters and sample size requirements discussed in the text are given herein. Additionally, the results of statistical analyses for evaluating homogeneity in recapture and survival probabilities, and in testing hypotheses of equality in parameter estimates under the simplified (H_O:P_A=P_D) versus the most generalized model (H_A:P_A P_D) are given.

The following terms are defined for the equations and likelihood functions which follow:

R_C	=	Number of control fish released
R_T	=	Number of treatment fish released
R	=	R_C=R_T
n	=	Number of replicate estimates $\hat{\tau}_i$ (*i*=1,…,n)
a_C	=	Number of control fish recaptured alive
d_C	=	Number of control fish recaptured dead
a_T	=	Number of treatment fish recaptured alive
d_T	=	Number of treatment fish recaptured dead
S	=	Probability fish survive from the release point of the controls to recapture
P_A	=	Probability an alive fish is recaptured
P_D	=	Probability a dead fish is recaptured
	=	Probability a treatment fish survives to the point of the control releases (*i.e.*, passage survival)
1-	=	Passage-related mortality.

The precision of the estimate was defined as:

$$P(-\varepsilon < \hat{\tau} - \tau < \varepsilon) = 1 - \alpha$$

or equivalently

$$P(-\varepsilon <| \hat{\tau} - \tau |< \varepsilon) = 1 - \alpha$$

where the absolute errors in estimation, *i.e.*, $|\hat{\tau} - \tau|$, is < (1-) 100% of the time, $\hat{\tau}$ is the estimated passage survival, and is the half-width of a (1-) 100% confidence interval for $\hat{\tau}$ or 1-$\hat{\tau}$. A precision of ±5%, 90% of the time is expressed as P($|\hat{\tau} - \tau|$<0.05)=0.90.

Using the above precision definition and assuming normality of $\hat{\tau} - \tau$, the required total sample size (R) is as follows:

$$P\left(\frac{-\varepsilon}{\sqrt{Var(\hat{\tau})}} < Z < \frac{\varepsilon}{\sqrt{Var(\hat{\tau})}}\right) = 1-\alpha$$

$$P\left(Z < \frac{-\varepsilon}{\sqrt{Var(\hat{\tau})}}\right) = \alpha/2$$

$$\Phi\left(\frac{-\varepsilon}{\sqrt{Var(\hat{\tau})}}\right) = \alpha/2$$

$$\frac{-\varepsilon}{\sqrt{Var(\hat{\tau})}} = Z_{\alpha/2}$$

$$Var(\hat{\tau}) = \frac{\varepsilon^2}{Z^2_{1-\frac{\alpha}{2}}}$$

$$\frac{\tau}{SP_A}\left[\frac{(1-S\tau P_A)}{R_T} + \frac{(1-SP_A)\tau}{R_C}\right] = \frac{\varepsilon^2}{Z^2_{1-\frac{\alpha}{2}}} \ .$$

where Z is a standard normal deviate satisfying the relationship $P(Z>Z_{1-\ /2})=\ /2$, and   is the cumulative distribution function for a standard normal deviate.

If data can be pooled across trials and letting $R_C=R_T=R$, the sample size for each release is

$$R = \frac{\tau}{SP_A}\left[1+\tau-2S\tau P_A\right]\frac{Z^2_{1-\alpha/2}}{\varepsilon^2} \ .$$

By rearranging, this equation can be solved to predetermine the anticipated precision given the available number of fish for a study. In most previous investigations (Normandeau Associates and Skalski 2000a) this equation has been used to calculate sample sizes because of homogeneity between trials; in the present investigation sample size was predetermined using this equation.

If data cannot be pooled across trials the precision is based on

$$\sum_{i=1}^{n}(1-\hat{\tau}_i)/n = 1-\sum_{i=1}^{n}\hat{\tau}_i/n = 1-\bar{\hat{\tau}} \ .$$

Precision is defined as

$$P(|\bar{\hat{\tau}}-\bar{\tau}| < \varepsilon) = 1-\alpha$$

$$P(-\varepsilon < \bar{\hat{\tau}}-\bar{\tau} | < \varepsilon) = 1-\alpha$$

$$P\left(\frac{-\varepsilon}{\sqrt{Var(\bar{\hat{\tau}})}} < t_{n-1} < \frac{\varepsilon}{\sqrt{Var(\bar{\hat{\tau}})}}\right) = 1 - \alpha$$

$$P\left(t_{n-1} < \frac{-\varepsilon}{\sqrt{Var(\bar{\hat{\tau}})}}\right) = \alpha / 2$$

$$\Phi\left(\frac{-\varepsilon}{Var(\bar{\hat{\tau}})}\right) = \alpha / 2$$

$$\frac{-\ \varepsilon}{\sqrt{Var(\bar{\hat{\tau}})}} = t_{\alpha/2,n-1}$$

$$Var(\bar{\hat{\tau}}) = \frac{\varepsilon^2}{t^2_{1-\alpha/2,n-1}}$$

$$\frac{\sigma^2_\tau + \frac{\tau}{SP_A}\left[\frac{(1 - S\tau P_A)}{R_T} + \frac{(1 - SP_A)\tau}{R_C}\right]}{n} = \frac{\varepsilon^2}{t^2_{1-\alpha/2,n-1}}$$

where ^{2}=natural variation in passage-related mortality.

Now letting R_T=R_C

$$\frac{\sigma^2_\tau + \frac{\tau}{SP_A}\left[\frac{(1 - S\tau P_A)}{R} + \frac{(1 - SP_A)\tau}{R}\right]}{n} = \frac{\varepsilon^2}{t^2_{1-\alpha/2,n-1}}$$

which must be iteratively solved for n given R. Or R given n where

$$R = \frac{\frac{\tau}{SP_A}\left[(1 - S\tau P_A) + (1 - SP_A)\tau\right]}{\left[\frac{n\varepsilon^2}{t^2_{1-\alpha/2,n-1}} - \sigma^2_\tau\right]}$$

$$R = \frac{\frac{\tau(1 + \tau)}{SP_A}}{\left[\frac{n\varepsilon^2}{t^2_{1-\alpha/2,n-1}} - \sigma^2_\tau\right]}$$

$$R = \frac{\tau(1+\tau)}{SP_A}\left[\frac{t^2_{1-\alpha/2,n-1}}{n\varepsilon^2 - \sigma^2_\tau t^2_{1-\alpha/2,n-1}}\right].$$

The joint likelihood for the passage-related mortality is:

$$L\ (S,\ \ ,P_A, P_D \mid R_C, R_T, a_C, a_T, d_C, d_T)=$$

$$\binom{R_C}{a_c d_C}(SP_A)^{a_C}((1-S)P_D)^{d_C}(1-SP_A-(1-S)P_D)^{R_C-a_C-d_C}$$

$$\times\binom{R_T}{a_T d_T}(S\tau P_A)^{a_T}((1-S\tau)P_D)^{d_T}(1-S\tau P_A-(1-S\tau)P_D)^{R_T-a_T-d_T}\ .$$

The likelihood model is based on the following assumptions: (1) fate of each fish is independent, (2) the control and treatment fish come from the same population of inference and share that same survival probability, (3) all alive fish have the same probability, P_A, of recapture, (4) all dead fish have the same probability, P_D, of recapture, and (5) passage survival ( ) and survival (S) to the recapture point are conditionally independent. The likelihood model has four parameters (P_A, P_D, S,) and four minimum sufficient statistics (a_C, d_C, a_T, d_T).

Because any two treatment releases were made concurrently with a single shared control group we used the likelihood model which took into account dependencies within the study design (Normandeau Associates *et al.* 1995). For any two treatment groups (denoted T_1 and T_2), the likelihood model is as follows:

$$L(S,\tau_1,\tau_2,P_A,P_D \mid R_C,R_{T_1},R_{T_2},a_C,d_c,a_{T_1},d_{T_1},a_{T_2},d_{T_2})=$$

$$\binom{R_C}{a_c d_C}(SP_A)^{a_C}((1-S)P_D)^{d_C}(1-SP_A-(1-S)P_D)^{R_C-a_C-d_C}$$

$$\times\binom{R_{T_1}}{a_{T_1} d_{T_1}}(S\tau_1 P_A)^{a_{T_1}}((1-S\tau_1)P_D)^{d_{T_1}}(1-S\tau_1 P_A-(1-S\tau_1)P_D)^{R_{T_1}-a_{T_1}-d_{T_1}}$$

$$\times\binom{R_{T_2}}{a_{T_2} d_{T_2}}(S\tau_2 P_A)^{a_{T_2}}((1-S\tau_2)P_D)^{d_{T_2}}(1-S\tau_2 P_A-(1-S\tau_2)P_D)^{R_{T_2}-a_{T_2}-d_{T_2}}\ .$$

This likelihood model has the same assumptions as stated in Normandeau Associates and Skalski (2000a) but has five estimable parameters (S, τ_1, τ_2, P_A, and P_D). The survival rate for treatment T_1 is estimated by τ_1 and for treatment T_2, by τ_2. A likelihood ratio test with 1 degree of freedom was used to test for equality in survival rates between treatments τ_1 and τ_2 based on the hypothesis H_O: $\tau_1 = \tau_2$ versus H_a: $\tau_1 \quad \tau_2$.

Likelihood models are based on the following assumptions: (a) the fate of each fish is independent; (b) the control and treatment fish come from the same population of inference and share the same natural survival probability, S; (c) all alive fish have the same probability, P_A, of recapture; (d) all dead fish have the same probability, P_D, of recapture; and (e) passage survival ( ) and natural survival (S) to the recapture point are conditionally independent.

The estimators associated with the likelihood model are:

$$\hat{\tau} = \frac{a_T R_C}{R_T a_C}$$

$$\hat{S} = \frac{R_T d_C a_C \text{ - } R_C d_T a_C}{R_C d_C a_T - R_C d_T a_C}$$

$$\hat{P}_A = \frac{d_C a_T \text{ - } d_T a_C}{R_T d_C - R_C d_T}$$

$$\hat{P}_D = \frac{d_C a_T \text{ - } d_T a_C}{R_C a_T - R_T a_C} \ .$$

The variance (Var) and standard error (SE) of the estimated passage mortality ($1 - \hat{\tau}$) or survival ($\hat{\tau}$) are:

$$Var(1-\hat{\tau}) = Var(\hat{\tau}) = \frac{\tau}{SP_A}\left[\frac{(1-S\tau P_{A)}}{R_T} + \frac{(1-SP_A)\tau}{R_C}\right]$$

$$SE(1-\hat{\tau}) = SE(\hat{\tau}) = \sqrt{Var(1-\hat{\tau})} \ .$$

DERIVATION OF VARIANCE FOR WEIGHTED AVERAGE SURVIVAL ESTIMATE

The variance of a weighted average is estimated by the formula

$$\hat{\bar{\theta}}_W = \frac{\sum_{i=1}^{n} W_i \hat{\theta}_i}{\sum_{i=1}^{n} W_i}$$

with

$$\mathrm{Var}\left(\hat{\bar{\theta}}_W\right) = \frac{\sum_{i=1}^{n} W_i \left(\hat{\theta}_i - \hat{\bar{\theta}}_W\right)^2}{(n-1)\sum_{i=1}^{n} W_i}$$

where $\hat{\bar{\theta}}_W$ = the weighted average,

$\hat{\theta}_i$ = the parameter estimate for the *i*th replicate,

W_i = weight.

APPENDIX C

HYDRAULIC/PHYSICAL CONDITIONS DURING TESTING IN MARCH AND MAY 2004

APPENDIX D

DAILY SURVIVAL CLEAN FISH AND INJURY DATA USED IN STATISTICAL ANALYSIS

APPENDIX E

DAILY FISH DISPOSITION DATA